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Interactive comment on "Quantifying the influence of CO_2 seasonality on future ocean acidification" *by* T. P. Sasse et al.

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Dear Editor,

Below follow comments on the manuscript: "Quantifying the influence of CO2 seasonality on future ocean acidification" by Sasse et al.

We thank the reviewers for their thorough comments and constructive suggestions. In our response below, we first address comments made by referee M. Hagens, followed by comments made by referee D.C.E Bakker. We hope the manuscript in its revised form will be accepted for publication in Biogeosciences.

Comments and responses to referee M. Hagens.

General comments:

- In my opinion, the manuscript would benefit from exploring changes in future ar seasonality. Previous work has shown that Ω will become more sensitive to changes in CT and AT, as the CT/AT ratio gets closer to unity due to enhanced atmospheric CO2 uptake (Egleston et al, 2010). As a result of this, Ωar seasonality is expected to increase during the 21st century until the point where CT equals AT, which, according to Egleston et al (2010), is reached at high latitudes around 3x the preindustrial pCO2 level (in this context, I could not follow the reasoning on p. 5918, lines 21-23). I understand the difficulties associated with predicting seasonality in carbonate system parameters using ESM and the choice of the authors to use decadal trends in CT and AT from the ESM to predict future Ωar. I would however encourage the authors to add some sensitivity analyses showing the potential effect of a shift in the phase and/or magnitude of CO2 seasonality, especially given that seasonality has been shown to be the dominant mode of contemporary ar variability in the majority of oceanic waters (Fig. 5).

- Response: As a first step to understanding the sensitivity of changes in seasonality we have included the following analysis and paragraph in the manuscript:

'As a first step in assessing the sensitivity of future ΩAr predictions to shifts in oceanic CO2 seasonality, we applied a similar approach described above to model output from 6 EMS (Table 2). In this approach, average seasonal cycles in CT, AT, temperature and salinity were first computed for the periods 2006 through 2015 and 2091 through 2100. Decadal-mean values from 2091-2100 were then added to the 2006-2015 seasonal cycles, thereby shifting the seasonal cycle to typical values of the years 2090-2100. Finally, seasonal ΩAr values were computed using both the average 2091-2100 and shifted 2006-2015 CT, AT, Temperature and Salinity values. Comparing the seasonal amplitudes in ΩAr found shifted values were on average 5.4% larger than the 2091-2100 average model output (sd = 48%), with individual model differences ranging from -0.4% to 19.1%. This suggests our data-based ΩAr amplitudes are on average 5.4% larger than expected if seasonality in CT, AT, temperature and salinity was taken into account.'

Understanding how the seasonal phase changes between the two approaches, while very interesting, is beyond the scope of this paper, as the focus of this paper is on the year at which under-saturation occurs, and not the exact month.

Specific comments:

-Manuscript title: the manuscript really focuses on the effects of CO2 seasonality on Ωar, not other impacts of OA. I would therefore suggest mentioning this more clearly in the title, e.g.: "Quantifying the influence of CO2 seasonality on future aragonite saturation"

-Response: We have changed the title from 'Quantifying the influence of CO2 seasonality on future ocean acidification' to 'Quantifying the influence of CO2 seasonality on future aragonite under-saturation onset'

-p. 5911, line 18: given that the CT climatologies represent the nominal year of 2000, why have decadal averages of temperature, salinity and nutrients been used rather than the 1995-2004 years?

- Response: CT climatologies represent the nominal year of 2000 since in-situ measurements collected between 1980 and 2011 were normalised to this year prior to deriving the empirical model by Sasse et al. (2013). By applying the empirical model to the WOA13 decadal averages instead of the 1995-2004 product eliminates the possibility of temporal bias in predicted CT and AT climatologies due to decadal variability in surface temperature, salinity and nutrients. To avoid confusion in the manuscript we have not included this information.

- p. 5912, lines 16-18: I agree that the winter pattern is well captured, with the possible exception of the winter zonal mean around 70S (is this also where the comment on p. 5914, lines 18-21, refers to?), but the summer zonal mean seems to be at the lower edge of the range of measurements around e.g. 60N and 40S. Do you have an

explanation for this?

- Response: This likely reflects the combination of spatial and temporal variability skewing the measurements compared to our zonal mean predictions. As referee D.C.E. Bakker correctly comments 'this is not comparing like to like'. To address this issue we have removed the in-situ measurements from figure 2, and added four figures comparing the winter- and summer-time in-situ measurements to the independent predictions in figure 3.

- p. 5915, line 6: it says here that the annual-mean values between 2006 and 2100 are used, but of which emission scenario? Were different results for IAV obtained when another scenario was used?

- Response: We have included details on the emission scenario used to obtain the model-based IAV estimates: 'we de-trended annual-mean projections from 2006 through to 2100 under the RCP8.5 emission scenario' We further applied the same analysis to the RCP4.5 and 2.6 emission scenarios. This showed insignificant differences between the three emission scenarios, we have included the following sentence 'These results are independent of the emission scenario used to calculate seasonal and inter-annual variability.'

- p. 5915, lines 26-28: is there a marked difference between the various ESM here? What is the spread in the various model-based relative to data-based seasonal amplitudes? p. 5917, lines 19-26: see general comment above.

- Response: We applied the same analysis to the 6 individual ESM and found similar results. We have included the following sentence in section 5 'We further applied this seasonal amplitude analysis to the 6 individual ESM (table 2) and found amplification factors ranged from 0.8 to 2.3 with a mean and standard deviation of 1.3$\pm$0.5.'

- p. 5918, lines 13-18: it is briefly mentioned that by including seasonality the onset of aragonite undersaturation in the Southern Ocean will be brought forward by ca. 8 years relative to the annual mean, while the situation of permanent undersaturation is delayed by ca. 15 years. I think this difference, resulting from the specific seasonal curve of Ωar at this location, is quite interesting and I'm wondering if this non-symmetrical pattern is also observed at other locations. Perhaps the authors could elaborate on this.

- Response: This response is related to the shape of the seasonality curve and will be different in different regions, as shown in the paper. However the goal of paper is not to discuss onset of permanent aragonite under-saturation, rather how its timing is changed by accounting for the seasonality. We've included the following description in the main paper and distribution plot of the year on permanent onset in the supplementary material.

'Wide-spread onset of permanent ΩAr under-saturation is only found in the Southern Ocean and Arctic Ocean by the year 2100 (see Fig. S5). In the Southern Ocean, the average time difference between annual-mean and permanent onset is 13.0$\pm$5.3 years, which is similar to the time difference between annual-mean and month-long onset at the same locations (13.0$\pm$5.9 years). Despite these similar basin-wide values, the correlation coefficient was found to be 0.31, indicating significant spatial differences. This reflects the non-symmetrical nature of seasonal ΩAr cycles in some regions of the Southern Ocean, as observed in Fig. 6b, which further highlights the importance of accounting for seasonal processes.'

- p. 5918, lines 21-23: see general comment above. With the projected greater sensitivity of Ωar to changes in CT and AT I would expect larger rather than smaller amplitudes. I would be interested in seeing the changes in both the Revelle factor and the amplitude of the Ωar seasonality, as it is not obvious from Fig. 6.

- Response: The discussion of changes in Revelle factor and its implications for future ΩAr seasonality would require an in-depth discussion that is beyond the scope of the current paper. We have therefore removed the paragraph noting that changes in ΩAr seasonality is related to shifts in the Revelle factor, as it is not directly relevant to our

results.

- p. 5920, lines 5-29: The results of RCP2.6 are presented in Table 2 and Fig. 8 but not discussed at all in this section. I would therefore include a short discussion on this scenario here. p. 5920, lines 27-29: in my opinion this is an interesting conclusion that could be stressed more, e.g. in the abstract.

- Response: We have included the following paragraph in Section 7.2:

'Under the RCP scenario whereby emissions are drastically reduced in the near future (RCP2.6), our results show very sparse under-saturation onset in the major ocean basins by the year 2100 (Fig. 8). In comparison with projections under RCP8.5, we find a 92.6% (or 83.6$\times$106 km2) reduction in global open-ocean surface waters exposed to at least month-long aragonite under-saturation within the 21st century. Regionally, this reduction increases to 98.9% (62.8$\times$106 km2), 92.8% (9.16$\times$106 km2) and 99.2% (6.8$\times$106 km2) in the Southern Ocean, North Pacific and North Atlantic respectively. This result emphasises the potential difference humanity can make by reducing our CO2 emissions.'

We have also included the following sentence in the conclusion:

'The spatial extent of ΩAr under-saturation is also drastically reduced under a lower emission scenario. Under RCP2.6 for example, our results show a 92.6% (or 83.6$\times$106 km2) reduction in open-ocean expose to ΩAr under-saturation compared to projections under RCP8.5, emphasising the importance of mitigating our CO2 emissions.'

Comments and responses to referee D.C.E. Bakker.

General comments:

Section 2 Methods

- P 5913 L10-11: The text should state CLEARLY that the uncertainties of 10.9 and 9.2 μmol/kg for DIC and TA are for the global ocean south of 70°N and exclude coastal waters (as is stated on page 4332, Figure 12 and Table 6 of Sasse et al., 2013a). The implication is that the results presented in this paper apply only for the global OPEN ocean south of 70°N. The authors might consider blanking areas for which the results are less accurate.

- Response: We have adjusted uncertainty estimates in DIC and TA to represent the global open-ocean region (80N to 80S) and clearly stated this in section 3 'within the global open-ocean'. We have also blanked areas which are less accurate (coastal waters) and excluded data within the coastal region from our analysis. It is important to note these changes did not affect our findings or conclusions due to the small amount of measurements removed.

- P5912. The error analysis of the monthly climatology for omega should be much more thorough.

- Response: We have included two additional error analyses in the main manuscript:

1) we partitioned the global independent ΩAr residual errors into 14 ocean regions to better evaluate spatial biases within our approach. This includes the addition of a table showing the RSE values for the 14 regions and the following discussion in section 3 'To assess for spatial biases, we partitioned the global independent predictions into 14 regions and calculated RSE values (Table 1; see Fig. S4 for regions). Here we find RSE values lie within $\pm$0.04 units of the global RSE ($\pm$0.14) in all regions except the Arctic Ocean, where the RSE value was found to be 0.22. In particular, the Southern Ocean is where our approach excels, predicting ΩAr values to within $\pm$0.10 units. The small variance of regional RSE values around the global RSE indicates no spatial bias.'

2) We have included residual standard error plots for summer and winter to assess the models ability to capture seasonal variability, and added the following sentence 'with winter-time and summer-time RSE values of 0.13 and 0.14 respectively (Fig. 3c,e), indicating no strong seasonal bias.'

- P5912. L2. Figure 1 is not very informative. More useful would be a difference plot between in situ measurements and predicted values. Better use might be made of the colour bar if it were to range from 1.0 to e.g. 4.5.

- Response: The purpose of figure 1 is to provide a general feel of our methods ability to capture spatial ΩAr variability, while section 3 provides an in-depth error analysis. We have therefore decided to not change Figure 1.

- P5912. L13 and Figure 2. The comparison of 'our zonal mean predictions to in situ measurements' is not comparing like with like. It would be instructive to 1) have a comparison of in situ predictions with in situ measurements for winter and summer and 2) zonal mean predictions for winter and summer (Figure 2).

- Response: We have followed this advice and adjusted the figures.

- P5912 L16. The wintertime minimum is clear for the northern hemisphere, but less so for the southern hemisphere.

- Response: This is consistent with our prediction of larger seasonal amplitudes in the northern hemisphere (see Figure 4). We have included the following sentence to comment on this connection: 'The stronger winter-time minimum for the Northern Hemisphere is consistent with our findings or larger seasonal amplitudes in the North Pacific and Atlantic compared to the Southern Ocean (see Fig. 4)'.

Section 3

- L5913. L13. The explanation of the independent predictions is far too short to be understandable. The reader should not have to read another paper to get the basics of this method.

- Response: We have included the following sentence to expand of the independent predictions approach: 'In their approach, measurements from each cruise (N=470) and time-series dataset (N=2) were individually excluded from the empirical model training phase, and then used as an independent dataset to predict CT and AT concentrations.

Here, we employ this dataset to calculate. . .'

- P5913. L23. This analysis does not provide any insight in to spatial biases in the approach, contrary to what the authors state. Extra information on spatial biases (or the absence thereof) would be beneficial.

- Response: We have provided extra information of spatial biases by including a table of regional RSE values and provided the following paragraph 'To assess for spatial biases, we partitioned the global independent predictions into 14 regions and calculated RSE values (Table 1; see Fig. S4 for regions). Here we find RSE values lie within ± 0.04 units of the global RSE (± 0.14) in all regions except the Arctic Ocean, where the RSE value was found to be 0.22. In particular, the Southern Ocean is where our approach excels, predicting ΩAr values to within ± 0.10 units. The small variance of regional RSE values around the global RSE indicates no spatial bias.'

Conclusions

- The conclusions are a summary of the text. This is not what conclusions should be like. The current conclusions are not very inspiring (as the article was very clear and informative). There is no need for the conclusions to repeat the introduction, nor to describe the methods. The conclusions should not repeat the main text and might be shortened substantially.

- Response: In response to the reviewers comment we have revised the conclusions:

'Ocean acidification is a global issue which is likely to impact the entire marine ecosystem - from plankton at the base of the food chain to fish at the top. Of particular concern is the decreasing concentration of CO3 ions, which lowers the saturation states of CaCO3 minerals (ΩAr and ΩCa) and results in detrimental seawater conditions for marine calcifiers (e.g. pteropods and corals; Aze et al., 2014; Fabry et al., 2008). Predicting when critical ΩAr threshold values will be reached is crucial for projecting the future health of marine ecosystems and for marine resources planning and manage-

ment. Here we have assessed how seasonality in oceanic CO2 will influence the future onset of ΩAr under-saturation.

The influence of seasonality was evaluated by comparing the difference in future month-long and annual-mean ΩAr under-saturation onset. Our results suggest seasonality brings forward the initial onset of month-long under-saturation by 17 years compared to annual mean estimates under RCP8.5, with differences extending up to 35 ± 17 years in the North Pacific due to strong regional seasonality. Our results also show large-scale under-saturation once atmospheric CO2 reaches 496ppm in the North Pacific, 517ppm in the North Atlantic and 511ppm in the Southern Ocean, independent of emission scenario. It's important to note that seasonality in these regions was also found to be the dominate mode of variability, accounting for $84\pm5\%$ of total model-based variability in the Southern Ocean (South of 30°S) and North Pacific (30°N to 70°N). This suggests IAV will not significantly alter onset times found in this study.

Under lower emission scenarios, the average time difference between month-long and annual-mean aragonite under-saturation onset increased from 14 years under RCP8.5 to 32 years under RCP4.5 in the Southern Ocean. This larger time difference under a lower emissions scenario emphasizes the importance of accounting for seasonality when projecting future OA levels under a slower emissions scenario. The spatial extent of ΩAr under-saturation is also drastically reduced under a lower emission scenario. Under RCP2.6 for example, our results show a 92.6% (or 83.6×106 km2) reduction in open-ocean expose to ΩAr under-saturation compared to projections under RCP8.5, emphasising the importance of mitigating CO2 emissions.

Seasonality also influences the spatial pattern of future ΩAr under-saturation, expanding the latitudinal extent by a global average of 3.5° (or 23×106 km2) towards the equator when compared to annual-mean projections under RCP8.5. From a biogeochemical perspective, this is particularly concerning given the regions of expansion form the poles ($\sim$40° to 50° South and North) are known as important hot-spots for CaCO3 export (Sarmiento and Gruber, 2006).

Finally, the implication of our results are not limited to the higher latitudes, strong ΩAr seasonality in some subtropical regions (30°S-30°N; see Fig. 4) will likely bring forward the onset of lower ΩAr waters by similar temporal periods. Since these regions are rich with sensitive calcifying coral reef ecosystems, considering the influence of seasonality is important when estimating future OA levels and their impacts in these regions.'

Minor comments:

Abstract:

- L5908 L16, L19, L21 Repetition: 'Our results suggest' (3x).

- Response: We have adjusted the abstract to reduce the use to 'Our results suggest'.

Introduction:

- P5908 L25. Consider adding a more recent reference.

- Response: We have updated the reference to the 2015 report.

- P5909. L2. Correct 'ocean's'

- Response: This has been corrected.

- P5910. L14. Consider adding a reference to Newton et al. (2014), the GOA-ON report to be found on this page.

- Response: We have included this reference

- P5910 L15-16. It is not clear what the authors want to say: such a large-scale initiative . . .throughout the global ocean'. Does the 2010 study really comment on the GOAON initiative (which started in or after 2010)?

- Response: We have adjusted the sentence:

'Despite significant efforts over recent years to establish a global carbon measurement network (e.g. the Global Ocean Acidification Observation Network; www.goa-on.org;

(Newton et al., 2014)), such a large-scale initiative remains very limited, resulting in only a limited understanding of CO2 seasonality throughout the global ocean'

to

'Despite significant efforts over recent years to establish a global carbon measurement network (e.g. the Global Ocean Acidification Observation Network; www.goa-on.org; (Newton et al., 2014)), such a large-scale initiative remains very limited due to spatial and temporal variability in oceanic CO2 coupled to the high cost of ship time, resulting in only a limited understanding of CO2 seasonality throughout the global ocean'

- P5911. L5, also P5917 and elsewhere. The authors refer to their TA and DIC climatologies as 'new global CO2 climatologies'. This is a little confusing.

- Response: We have clarified these sentences by changing 'the new global climatologies' to 'the global climatologies of Sasse et al.'.

Section 2:

- P5911. L12. Correct 'ocean's'.

- Response: This has been corrected.

- P5912. L23. Is Popova et al (2014) a 'data-based' study? While glancing over it, I could not find much evidence of data being the basis of the (model?) predictions.

- Response: We have modified this sentence to read 'which is consistent with previous data-based (e.g. Mathis and Questel, 2013) and model-based (e.g. Popova et al., 2014) studies.'

Section 3:

- P5913. L21. The figures present a near-normal distribution, not a normal distribution as stated in the text.

- Response: We have adjusted 'followed a normal distribution' to 'followed a near normal distribution'

Section 5:

- P5914. L25. Diurnal variation can play a role in open ocean areas with shallow mixed layers, such as the tropics. There is some older work on this (e.g. Robertson et al., 1993; Bakker et al., 2001; Boutin et al., 1998). Recent studies on surface salinity in a SMOS context are also looking into this (talks at 2014 ESA-SOLAS-EGU conference).

- Response: We have changed 'Variability in the open-ocean CO2 system is the combination of seasonal and inter-annual variability' to 'Variability in the open-ocean CO2 system is driven mainly by seasonal and inter-annual variability'. However we maintain that diurnal variability is likely only significant in the coastal domains.

- P5914. L25. Not sure whether (Aze et al. 2014) is the correct way of citing the CBD report. I suspect that the 3 editors played a key role in this report. The report itself provides this citation (page 2): Secretariat of the Convention on Biological Diversity (2014). An Updated Synthesis of the Impacts of Ocean Acidification on Marine Biodiversity (Eds: S. Hennige, J.M. Roberts & P. Williamson). Montreal, Technical Series No. 75, 99 pages.

- Response: This reference has been updated.

- P5915. L8. Did you explain SD?

- Response: We have included a definition of SD (standard deviation).

- P5915. L14. Clarify that this is 'seasonality is the dominant mode of variability throughout the global ocean in the models'. (add 'in the models'.)

- Response: We have changed 'This analysis revealed that seasonality is the dominate mode of variability' to 'This model-based analysis shows seasonality to be the dominate mode of variability'.

- P5915. L24. 'consistent' appears to overstate this pattern. Consider replacing 'consistent' by 'similar'.

- Response: 'Consistent' has been replaced with 'similar'

- P5915. L27. What is the standard deviation (or the range) of the ratio of 1.3?

- Response: We have included the standard deviation (sd = 0.5).

- P5916. L1. Add 'This suggests ESM on average under-predict'.

- Response: We have added 'on average'.

Section 6:

- P5916. L13. The authors casually state that surface ocean pCO2 would track the increase in atmospheric CO2. What is this statement based on? Clarify which implicit assumptions this statement relies on. Add a reference.

- Response: We have added 'regionally integrated' and 'over longer timescales' into the following sentence to clarify: 'the rate of increase in regionally integrated ocean surface pCO2 would have roughly tracked the atmospheric CO2 growth rate over longer timescales'. We have also included the reference (Lenton et al., 2012; Tjiputra et al., 2014).

- P5916. L13-14. The authors state that this was 'likely adequate for most of the 20th century'. What do the authors mean with 'likely adequate'? What do the authors base this statement on? Is this a model result? If so, say so. Only in recent decades is data coverage of ocean carbon parameters sufficiently large for trend analysis of surface ocean CO2 (e.g. Takahashi et al., 2009).

- Response: We have omitted the sentence 'Although this was likely adequate for most of the 20th century'. This sentence is not necessary and confuses the message.

- P5917. L2. The authors mention an increase in the CO2 disequilibrium. What is this based on? A reference would be appropriate.

- Response: We have included ‘described above’ to clarify what this is based on, and added the reference (McNeil and Matear, 2013).

Section 7:

- P5918. L8. Why are these sites ‘unique’? Consider removing the word ‘unique’. Presumably you mean that these are ‘single’ sites, but that these sites are somewhat representative for the wider region.

- Response: We have changed ‘unique’ to ‘1°x1°’ and included ‘which are somewhat representative of the larger region’

- P5918. L21-23. The statement on a reduction in seasonal amplitudes of omega as a result of changes in the Revelle factor needs better explanation and possibly a reference to earlier studies observing something similar. The current text is rather cryptic.

- Response: The discussion of changes in Revelle factor and its implications for future ΩAr seasonality would require an in-depth discussion that is beyond the scope of the current paper. We have therefore removed the paragraph noting that changes in ΩAr seasonality is due to shifts in the Revelle factor, as it is not directly relevant to our results.

- P5919. L3-4 and L11. Add ‘the year’, in ‘by the year 2086’ and ‘as early as the year 2030’.

- Response: These have been added

- P5919. L5. Correct ‘century’s’. (??)

- Response: We have change ‘centuries end’ to ‘the year 2100’

- P5920. L2. Remove ‘before this occurs’ as this overlaps with ‘before’ later in the sentence.

- Response: This sentence has been adjusted accordingly.

- P5920. L21. Add ‘the’ in ‘the Southern Ocean’.

- Response: ‘the’ has been added.

Section 8:

- Section 8. P5921. L8. Do you mean ∼3.5° latitude’? Clarify.

- Response: we have changed ‘increases by ∼3.5°’ to ‘shifted equatorward by ∼3.5° degrees’

- P5921 L10. Remove ‘additional’. This is not really additional.

- Response: ‘an additional’ has been removed.

- P5921. L13. ‘Much earlier than anticipated’. What is this based on? Clarify.

- Response: We have included ‘under previous annual-mean projections (e.g. Orr et al. 2005).’ To clarify.

Conclusions:

- P5921 L20. Remove or clarify ‘at the base’ and ‘at the top’.

- Response: We have included ‘of the food chain’ to clarify.

- P5921 L21-L22. Saturation states and minerals are plural, however, you only provide the symbol for omega aragonite. Correct.

- Response: ‘and ΩCa’ was added.

References:

Secretariat of the Convention on Biological Diversity (2014), An Updated Synthesis of the Impacts of Ocean Acidification on Marine Biodiversity, (Eds: Hennige, S., Roberts, J. M., and Williamson, P.), Montreal, Technical Series no. 75, 99 pp.

Fabry, V. J., Seibel, B. A., Feely, R. A., and Orr, J. C. (2008), Impacts of ocean acidification on marine fauna and ecosystem processes, ICES Journal of Marine Science / Journal du Conseil, 65, 414-432, DOI: 10.1093/icesjms/fsn048

Lenton, A., Metzl, N., Takahashi, T., Kuchinke, M., Matear, R. J., Roy, T., Sutherland, S. C., Sweeney, C., and Tilbrook, B. (2012), The observed evolution of oceanic pCO2 and its drivers over the last two decades, Global Biogeochem. Cycles, 26, GB2021, DOI: 10.1029/2011gb004095

Mathis, J. T., and Questel, J. M. (2013), Assessing seasonal changes in carbonate parameters across small spatial gradients in the Northeastern Chukchi Sea, Continental Shelf Research, 67, 42-51, DOI: 10.1016/j.csr.2013.04.041

McNeil, B. I., and Matear, R. J. (2013), The non-steady state oceanic CO2 signal: its importance, magnitude and a novel way to detect it, Biogeosciences, 10, 2219-2228, DOI: 10.5194/bg-10-2219-2013

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Popova, E. E., Yool, A., Aksenov, Y., Coward, A. C., and Anderson, T. R. (2014), Regional variability of acidification in the Arctic: a sea of contrasts, Biogeosciences, 11, 293-308, DOI: 10.5194/bg-11-293-2014

Sarmiento, J. L., and Gruber, N. (2006), Ocean biogeochemical dynamics, Princeton University Press, 526 pp.

Tjiputra, J. F., Olsen, A., Bopp, L., Lenton, A., Pfeil, B., Roy, T., Segschneider, J., Totterdell, I., and Heinze, C. (2014), Long-term surface pCO2 trends from observations and models, Tellus B, DOI: 10.3402/tellusb.v66.23083

Interactive comment on Biogeosciences Discuss., 12, 5907, 2015.

Region	Zone[a]	RSE[b]	N[c]
Arctic Ocean	1	0.22	673
Sup-Polar North Atlantic	2	0.13	2380
Sub-Tropical North Atlantic	3	0.11	1205
Equatorial Atlantic	4	0.16	565
Sub-Tropical South Atlantic	5	0.12	527
Sub-Polar North Pacific	6	0.18	1541
Sub-Tropical North Pacific	7	0.15	1412
Equatorial Pacific	8	0.16	764
Sub-Tropical South Pacific	9	0.15	1353
Sub-Tropical North Indian	10	0.13	137
Equatorial Indian	11	0.13	481
Sub-Tropical South Indian	12	0.11	1340
Southern Ocean	13	0.10	2923
Subantarctic waters	14	0.11	1426
Global		**0.138**	**16727**

Table 1: Regional and global skill evaluation for predicting Ω_{Ar} (see Fig. S3 for map of spatial division).

[a] Corresponding geographical region in Fig. S3

[b] Residual Standard Error

[c] number of measurements

Fig. 1.

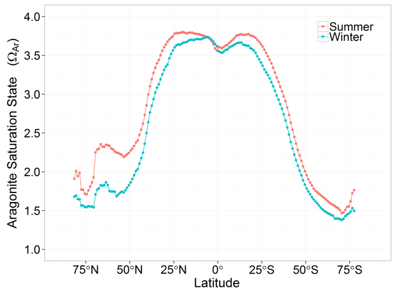

Figure 2: Zonal mean Ω_{Ar} predictions for winter and summer (joined dots). Summer and winter months were defined as June through to August and December through to February for Northern Hemisphere respectively, while Southern Hemisphere differed by 6 months.

Fig. 2.

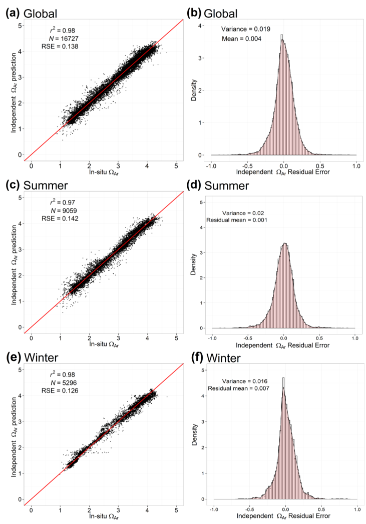

Figure 3: Statistical plots comparing global Ω_{Ar} values calculated via the in-situ network of C_T and A_T measurements, and independently predicted C_T and A_T values via the approach of Sasse et al (2013b). (a) Global independent predictions versus in-situ values, where the red line represents y = x relationship (b) Global distribution of the independent residual errors (c,e) Winter and Summer independent predictions versus in-situ values (d,f) Winter and Summer distribution of the independent residual errors. Summer and winter months were defined as June through to August and December through to February for Northern Hemisphere respectively, while Southern Hemisphere differed by 6 months.

Fig. 3.

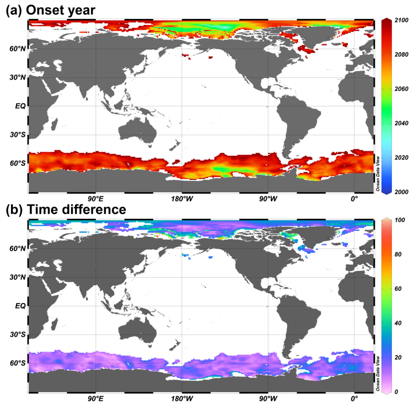

Figure S5: (a) Estimated onset year for permanent aragonite under-saturation under RCP8.5. (b) Time difference (years) between annual-mean and permanent onset.

Fig. 4.